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# Measurement of the shape of the boson transverse momentum distribution in $p\bar{p} \to Z/\gamma^* \to e^+e^- + X$ events produced at $\sqrt{s} = 1.96$ TeV

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We present a measurement of the shape of the $Z/\gamma^*$ boson transverse momentum ($q_T$) distribution in $p\bar{p} \to Z/\gamma^* \to e^+e^- + X$ events at a center-of-mass energy of 1.96 TeV using 0.98 fb$^{-1}$ of data

collected with the D0 detector at the Fermilab Tevatron collider. The data are found to be consistent with the resummation prediction at low $q_T$, but above the perturbative QCD calculation in the region of $q_T > 30$ GeV/$c$. Using events with $q_T < 30$ GeV/$c$, we extract the value of $g_2$, one of the non-perturbative parameters for the resummation calculation. Data at large boson rapidity $y$ are compared with the prediction of resummation and with alternative models that employ a resummed form factor with modifications in the small Bjorken $x$ region of the proton wave function.

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A complete understanding of weak vector boson production is essential for maximizing the sensitivity to new physics at hadron colliders. Studies of the $Z/\gamma^*$ boson production play a particularly valuable role in that its kinematics can be precisely determined through measurement of its leptonic decays. Throughout this Letter, we use the notation "$Z$ boson" to mean "$Z/\gamma^*$ boson", unless specified otherwise.

$Z$ boson production also serves as an ideal testing ground for predictions of quantum chromodynamics (QCD), since the boson's transverse momentum, $q_T$, can be measured over a wide range of values and can be correlated with its rapidity. At large $q_T$ (approximately greater than 30 GeV/$c$), the radiation of a single parton with large transverse momentum dominates the cross section, and fixed-order perturbative QCD (pQCD) calculations [1, 2], should yield reliable predictions. At lower $q_T$, multiple soft gluon emission can not be neglected, and the fixed-order perturbation calculation no longer gives accurate results. A soft-gluon resummation technique developed by Collins, Soper, and Sterman (CSS) [3] gives reliable predictions in the low-$q_T$ region. A prescription has been proposed [4] for matching the low- and high-$q_T$ regions in order to provide a continuous prediction for all values of $q_T$. The CSS resummation formalism allows the inclusion of contributions from large logarithms of the form $\ln^n(q_T^2/Q^2)$ to all orders of perturbation theory in an effective resummed form factor, where $Q^2$ represents the invariant mass corresponding to the four-momentum transfer. The CSS resummation can be done either in impact parameter ($b$) space or in transverse momentum ($q_T$) space. In the case of $b$-space resummation, this form factor can be parameterized with the following non-perturbative function first introduced by Brock, Landry, Nadolsky and Yuan (BLNY) [5]:

$$S_{NP}(b, Q^2) = \left[g_1 + g_2 \ln\left(\frac{Q}{2Q_0}\right) + g_1 g_3 \ln(100 x_i x_j)\right] b^2, \tag{1}$$

where $x_i$ and $x_j$ are the fractions of the incident hadron momenta carried by the colliding partons, $Q_0$ is a scale typical of the onset of non-perturbative effects, and $g_1$, $g_2$ and $g_3$ are phenomenological non-perturbative parameters that must be obtained from fits to the data. The $Z$ boson $q_T$ distribution at the Fermilab Tevatron is by far most sensitive to the value of $g_2$ and quite insensitive to the value of $g_3$. Thus a measurement of the $Z$ boson $q_T$ spectrum can be used to test this formalism and to determine the value of $g_2$.

Recent studies of data from deep inelastic scattering (DIS) experiments [6, 7] indicate that the resummed form factor in the above equation may need to be modified for processes involving a small-$x$ parton in the initial state. Ref. [8] indicates how such a modification would influence the $q_T$ distributions of vector and Higgs bosons produced in hadronic collisions. A wider $q_T$ distribution is predicted for $Z$ bosons with large rapidity (called "small-$x$ broadening"). $Z$ bosons produced at the Tevatron in the rapidity range $2 < |y| < 3$ probe processes involving a parton with $0.002 < x < 0.006$, and can be used to test the modified form factor at small $x$.

$Z$ boson $q_T$ distributions have been published previously by the CDF [9] and D0 [10] collaborations using about 100 pb$^{-1}$ of data at $\sqrt{s} = 1.8$ TeV. In this Letter, we report a new measurement with larger statistics and improved precision. This measurement is also the first to present a $q_T$ distribution for large-rapidity $Z$ bosons. The data sample used in this measurement was collected using a set of inclusive single-electron triggers with the D0 detector [11] at the Fermilab Tevatron collider, and the integrated luminosity is $980 \pm 60$ pb$^{-1}$ [12].

Our selection criteria for $Z$ bosons require two isolated electromagnetic clusters that have a shower shape consistent with that of an electron. Electron candidates are required to have transverse momentum greater than 25 GeV/$c$. The electron pairs must have a reconstructed invariant mass $70 < M(ee) < 110$ GeV/$c^2$. If an event has both its candidate electrons in the central calorimeter (CC events), each electron must be spatially matched to a reconstructed track. Because the tracking efficiency decreases with rapidity in the endcap region, events with one or two endcap calorimeter electron candidates (CE and EE events, respectively) are required to have at least one electron with a matching track. After these requirements, 23,959 CC, 30,344 CE, and 9,598 EE events are selected; 5412 of these have a reconstructed $Z$ boson with $|y| > 2$.

Electron identification efficiencies are measured using a combination of data and a GEANT-based [13] simulation of the D0 detector. The electron identification efficiencies are measured from $Z$ data. The dependence of the overall selection efficiency on the $Z$ boson $q_T$ is parameterized from the GEANT simulation. A measurement of this shape from the data agrees well with the simulation within statistical uncertainties.

The dominant backgrounds are from photon plus jet events and di-jet events, with photons and jets misidentified as electrons. The kinematic properties of these events are obtained from events that satisfy most of the $Z$ selection criteria, but fail the electron shower shape requirement. The normalization of the background is obtained by fitting to a sum of a signal shape obtained from a parameterized simulation of the detector response and the invariant mass distribution from the background sample to the invariant mass distribution of the data sample. The background fractions are $(1.30\pm0.14)\%$, $(8.55\pm0.26)\%$, and $(4.71\pm0.30)\%$ for CC, CE, and EE events respectively. Other backgrounds are negligible.

The data are corrected for acceptances within a range of generated $Z$ masses of 40 to 200 GeV/$c^2$, and for selection efficiencies using a parameterized simulation. We use ResBos [14] as the event generator which incorporates the resummation calculation in $b$-space using the BLNY parameterization for low $q_T$ and a NLO pQCD calculation for high $q_T$. We use PHOTOS [15] to simulate the effects of final state photon radiation. The overall acceptance times efficiency falls slowly from a value of 0.27 at low $q_T$ to a minimum of 0.19 at $q_T = 40$ GeV/$c$ and slowly increases for larger $q_T$.

The measured spectrum is further corrected for detector resolution effects using the RUN (Regularized Unfolding) program [16] to obtain the true differential cross section. Its performance was verified by comparing the true and unfolded spectrum generated using pseudo-experiments. The measured $Z$ $q_T$ resolution is about 2 GeV/$c$; the bin width we choose is 2.5 GeV/$c$ for $q_T < 30$ GeV/$c$. The typical correlation between adjacent bins is around 30%. Due to limited statistics, the chosen bin width is 10 GeV/$c$ for $30 < q_T < 100$ GeV/$c$ and 40 GeV/$c$ for $100 < q_T < 260$ GeV/$c$.

Systematic uncertainties on the unfolded $q_T$ spectrum arise from uncertainties on the electron energy calibration, the electron energy resolution, the dependence of the overall selection efficiency on $q_T$, and the effect of parton distribution functions (PDFs) on the acceptance. The uncertainties on the unfolded spectrum are estimated from the resulting change when the smearing parameters are varied within their uncertainties. CTEQ 6.1M is used as the default PDF. Uncertainties due to the PDFs are estimated using the procedure described in Ref. [17]. The uncertainty due to the choice of unfolding parameters in the RUN program is also estimated and included in the final systematic uncertainty.

The final results in the $q_T < 30$ GeV/$c$ range, are shown in Fig. 1 for the inclusive sample and for the sample with $|y| > 2$. Each data point is plotted at the average value of the expected distribution over the bin [18]. For the theoretical calculation, we use ResBos with published values of the non-perturbative parameters [5]. Good agreement between data and the prediction is observed for all rapidity ranges, which indicates that the BLNY parameterization works well for the low $q_T$ region.

$Z$ boson events produced at large rapidities ($|y| > 2$) are also used to test the small-$x$ prediction. We compare data with the theoretical predictions with and without the form factor as modified from studies of small-$x$ DIS data [8]. All curves are normalized to 1 for $q_T < 30$ GeV/$c$. The default values for the parameters $g_1$, $g_2$, and $g_3$ [5] obtained from large-$x$ data are used. The $\chi^2$/d.o.f. between the data and the ResBos calculation using the default parameters is 0.8/1 for $q_T < 5$ GeV/$c$ and 11.1/11 for $q_T < 30$ GeV/$c$, while that for the modified calculation is 5.7/1 for $q_T < 5$ GeV/$c$ and 31.9/11 for $q_T < 30$ GeV/$c$. It remains to be seen if retuning of the non-perturbative parameters could improve the agreement for the modified calculations.

Figure 2 shows the measured differential cross section in the range $q_T < 260$ GeV/$c$ compared to (1) the ResBos calculation with its default parameters [5], (2) ResBos with a NLO to NNLO K-factor by Arnold and Reno [19] incorporated into ResBos by its authors, (3) a pQCD calculation at NNLO [2] using the MRST 2001 NNLO PDF set [20] divided by the NNLO calculation of the total cross section [21], and (4) the NNLO calculation but rescaled to the data at $q_T = 30$ GeV/$c$. The agreement between data and ResBos, with or without the K-factor, is good for $q_T < 30$ GeV/$c$. At higher values of $q_T$, the data are not in agreement with the ResBos calculation. The data agree better with the NNLO calculation and ResBos prediction with the Arnold-Reno K-factor, but agrees best when the NNLO results are rescaled by a factor of 1.25 so that they match the data at $q_T = 30$ GeV/$c$. This indicates that the shape from these calculations agrees with the data, and that the source of the discrepancy is in the normalization. Table I summarizes the measured values for each $q_T$ bin together with statistical and systematic uncertainties.

The CSS model parameter most sensitive to the shape at low $q_T$ ($q_T < 30$ GeV/$c$) is $g_2$. In a fit, we fix other phenomenological parameters to the values obtained in Ref. [5] and only vary $g_2$. A minimum $\chi^2$/d.o.f. of 9/11 between the model and the inclusive data for $q_T < 30$ GeV/$c$ is found when $g_2 = 0.77 \pm 0.06$ (GeV/$c$)$^2$.

In conclusion, we have measured the normalized differential spectrum, $\frac{1}{\sigma}\frac{d\sigma}{dq_T}$, for $Z$ boson events produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with boson mass $40 < M < 200$ GeV/$c^2$ and $q_T < 260$ GeV/$c$. This represents the highest center-of-mass energy measurement of this quantity over the largest phase space available to date. The overall uncertainty of this measurement has been reduced compared with the previous measurements. We find that for $q_T < 30$ GeV/$c$, the CSS resummation model used in ResBos describes the data very well at all rapidities. Our data with $|y| > 2$ disfavor a variant of this model that incorporates an additional small-$x$ form factor when $g_1$, $g_2$, and $g_3$ from large-$x$ data is used. Using the BLNY parameterization for events with $q_T < 30$ GeV/$c$,

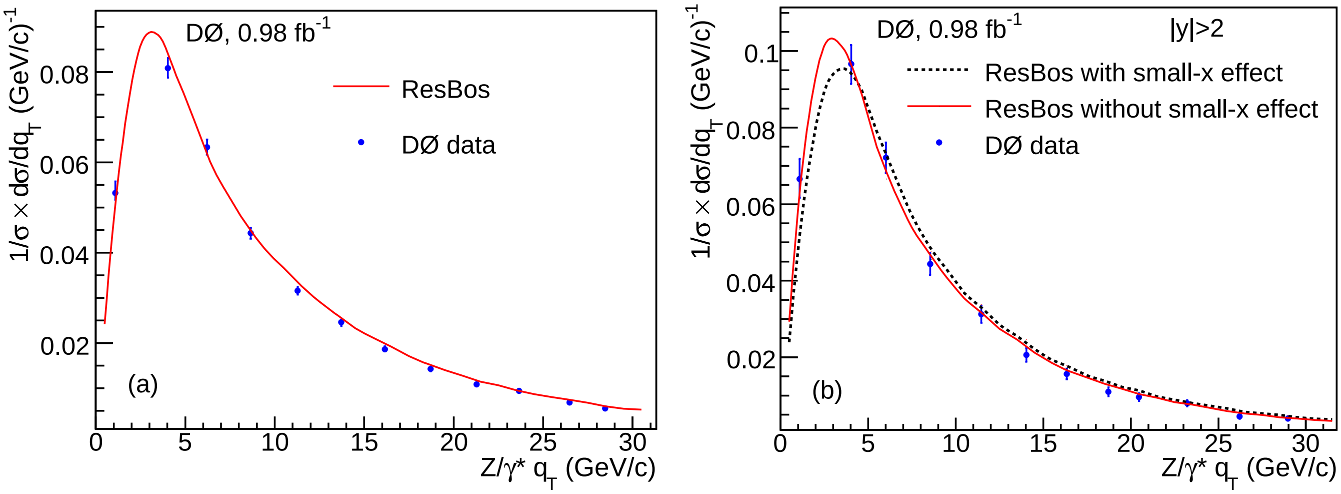


FIG. 1: The normalized differential cross section as a function of $q_T$ for (a) the inclusive sample and (b) the sample with $Z$ boson $|y| > 2$ with $q_T < 30$ GeV/$c$. The points are the data, the solid curve is the ResBos prediction, and the dashed line in (b) is the prediction from the form factor modified after studies of small-$x$ DIS data.

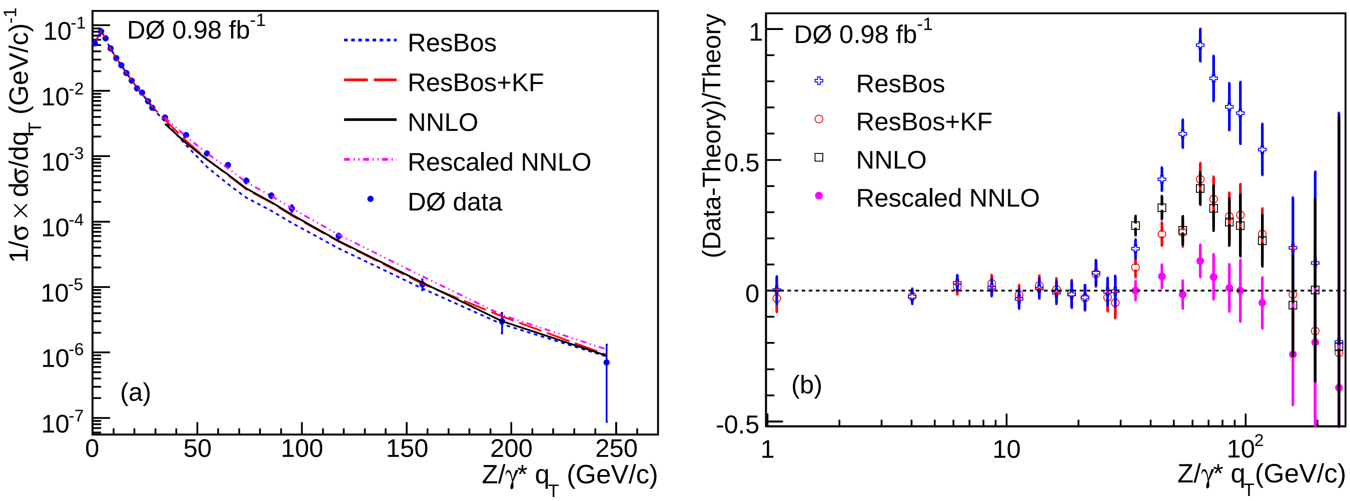


FIG. 2: The normalized differential cross section as a function of $q_T$ compared to four theoretical calculations for (a) the entire range measured and (b) the fractional differences between data and the theoretical predictions. The four theoretical calculations are ResBos with its default parameters, ResBos with a NLO to NNLO K-factor by Arnold and Reno, the NNLO calculation by Melnikov and Petriello, and the NNLO calculation but rescaled to data at $q_T = 30$ GeV/$c$.

we obtain $g_2 = 0.77 \pm 0.06$ (GeV/$c$)$^2$, which is comparable with the current world average value [5]. We observe a disagreement between our data and NNLO calculations in the region $q_T > 30$ GeV/$c$, where our distribution is higher than predicted by a factor of 1.25. However, the NNLO calculation agrees in shape with our data when normalized at $q_T = 30$ GeV/$c$.

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| $\langle q_T \rangle$ (GeV/$c$) | $1/\sigma \times d\sigma/dq_T$ (GeV/$c$)$^{-1}$ |
|---|---|
| 1.1 | $(5.32 \pm 0.13 \pm 0.24) \times 10^{-2}$ |
| 4.0 | $(8.08 \pm 0.12 \pm 0.19) \times 10^{-2}$ |
| 6.2 | $(6.33 \pm 0.11 \pm 0.14) \times 10^{-2}$ |
| 8.7 | $(4.43 \pm 0.09 \pm 0.11) \times 10^{-2}$ |
| 11.3 | $(3.15 \pm 0.08 \pm 0.08) \times 10^{-2}$ |
| 13.7 | $(2.46 \pm 0.07 \pm 0.06) \times 10^{-2}$ |
| 16.2 | $(1.86 \pm 0.06 \pm 0.05) \times 10^{-2}$ |
| 18.7 | $(1.42 \pm 0.05 \pm 0.05) \times 10^{-2}$ |
| 21.3 | $(1.09 \pm 0.04 \pm 0.03) \times 10^{-2}$ |
| 23.7 | $(9.40 \pm 0.40 \pm 0.20) \times 10^{-3}$ |
| 26.4 | $(6.90 \pm 0.30 \pm 0.20) \times 10^{-3}$ |
| 28.5 | $(5.50 \pm 0.30 \pm 0.10) \times 10^{-3}$ |
| 34.6 | $(3.90 \pm 0.10 \pm 0.10) \times 10^{-3}$ |
| 44.6 | $(2.10 \pm 0.07 \pm 0.06) \times 10^{-3}$ |
| 54.6 | $(1.10 \pm 0.05 \pm 0.03) \times 10^{-3}$ |
| 64.6 | $(7.30 \pm 0.40 \pm 0.20) \times 10^{-4}$ |
| 73.4 | $(4.20 \pm 0.30 \pm 0.20) \times 10^{-4}$ |
| 85.4 | $(2.50 \pm 0.20 \pm 0.10) \times 10^{-4}$ |
| 95.1 | $(1.60 \pm 0.17 \pm 0.08) \times 10^{-4}$ |
| 117.5 | $(6.00 \pm 0.50 \pm 0.30) \times 10^{-5}$ |
| 157.5 | $(1.10 \pm 0.20 \pm 0.07) \times 10^{-5}$ |
| 195.5 | $(3.00 \pm 1.00 \pm 0.30) \times 10^{-6}$ |
| 245.5 | $(7.10 \pm 6.10 \pm 0.60) \times 10^{-7}$ |

TABLE I: The normalized differential cross section for $Z$ events produced in bins of $q_T$. The first uncertainty is statistical and the second is systematic.

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[c] Visitor from ICN-UNAM, Mexico City, Mexico.
[d] Visitor from II. Physikalisches Institut, Georg-August-University Göttingen, Germany.
[e] Visitor from Helsinki Institute of Physics, Helsinki, Finland.
[f] Visitor from Universität Zürich, Zürich, Switzerland.
[†] Fermilab International Fellow.
[‡] Deceased.

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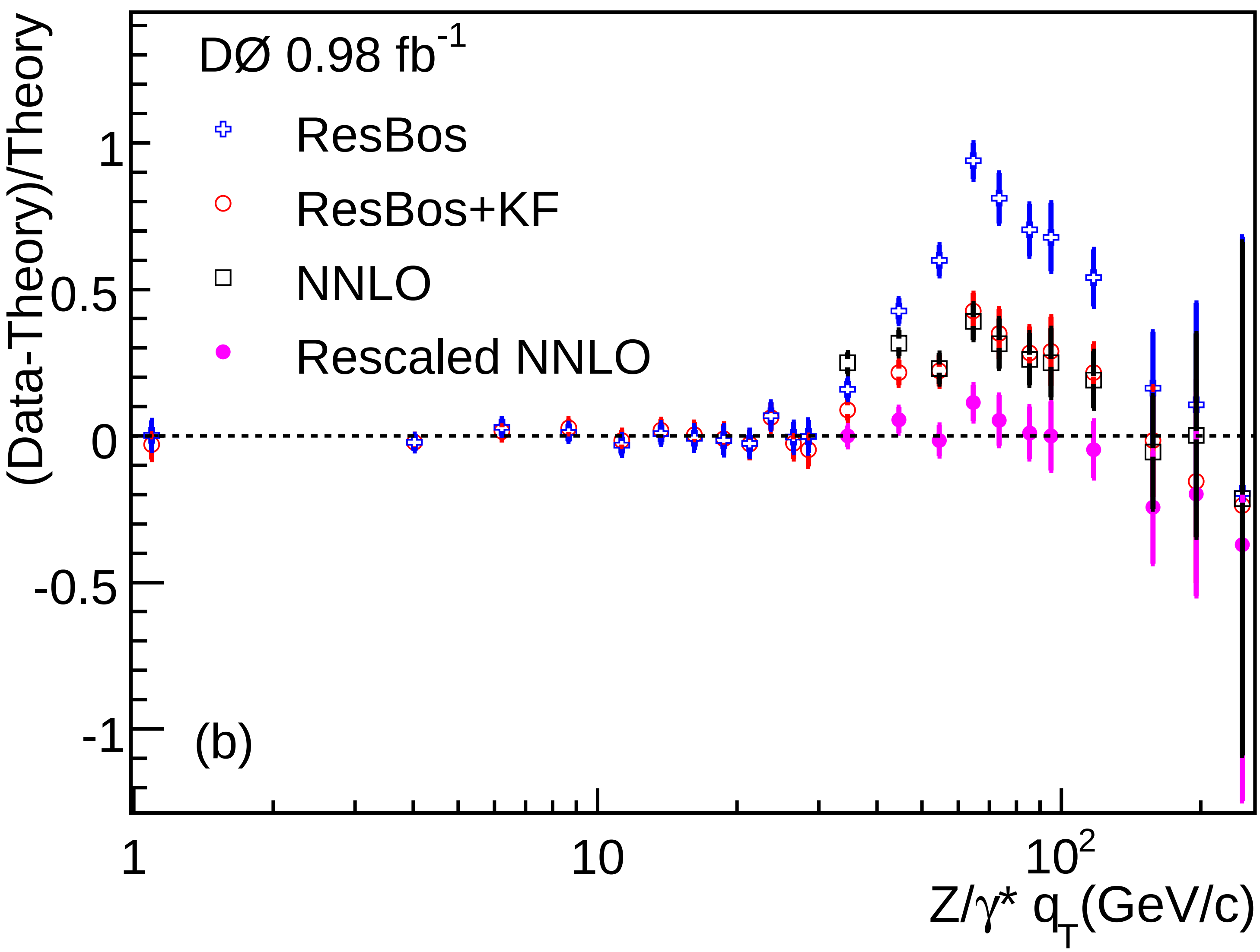
DØ 0.98 fb$^{-1}$
ResBos
ResBos+KF
NNLO
Rescaled NNLO
(b)
(Data-Theory)/Theory
Z/γ* $q_T$(GeV/c)
1
0.5
0
-0.5
-1
1
10
$10^2$